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[54] CATADIOPTRIC REDUCTION PROJECTION OPTICAL SYSTEM AND EXPOSURE APPARATUS HAVING THE SAME

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[52] U.S. Cl. 359/727; 359/720
[58] Field of Search 359/70, 77

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5,220,454 6/1993 Ichihara et al. .
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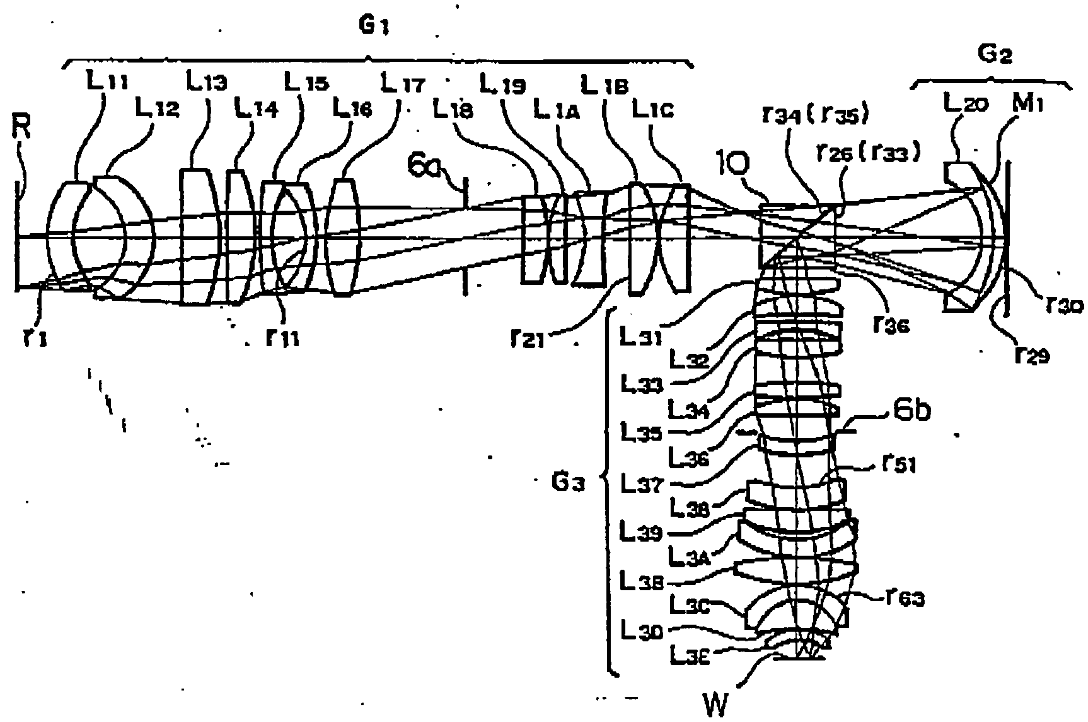
[57] ABSTRACT

A catadioptric projection optical system is provided, which can use a beam splitting optical system smaller in size than a conventional polarizing beam splitter, can set a long optical path from a concave reflecting mirror to an image plane, allows easy adjustment of the optical system, and has excellent imaging performance. A light beam from an object surface forms a first intermediate image through a refracting lens group. A light beam from the first intermediate image passes through a polarizing beam splitter and is reflected by a concave reflecting mirror to form a second intermediate image in the polarizing beam splitter. A light beam from the second intermediate image is reflected by the polarizing beam splitter means to form a final image on the image plane via a refracting lens group. The polarizing beam splitter means is arranged near the positions at which the intermediate images are formed.

14 Claims, 13 Drawing Sheets



CATADIOPTRIC REDUCTION PROJECTION OPTICAL SYSTEM AND EXPOSURE APPARATUS HAVING THE SAME

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a catadioptric reduction optical system suitably applied to a projection optical system for reduction projection in a projection exposure apparatus of a one-shot exposure method or a scanning exposure method, used to manufacture a semiconductor element or a liquid crystal display element in a photolithographic process and, more particularly, to a catadioptric reduction projection optical system having a magnification of about 1/4 to 1/5 with a resolution on the submicron order in the ultraviolet wavelength range.

2. Related Background Art

In fabricating semiconductor devices or liquid crystal display devices, etc. by photolithography process, the projection exposure apparatus is used for demagnifying through a projection optical system a pattern image on a reticle (or photomask, etc.) for example at a ratio of about 1/4 to 1/5 to effect exposure of the image on a wafer (or glass plate, etc.) coated with a photoresist and the like.

With the recent increase in the integration degree of semiconductor elements and the like, a higher resolution is required for a projection optical system used in a projection exposure apparatus. In order to meet this requirement, the wavelength of illumination light (exposure wavelength) for exposure must be shortened, or the numerical aperture (NA) of the projection optical system must be increased. If, however, the exposure wavelength is shortened, the types of optical glass which can be used in practice are limited because of the absorption of illumination light. In particular, as the exposure wavelength becomes 300 nm or less, only synthetic quartz and fluorite can be used in practice as glass materials.

The difference between the Abbe constants of the synthetic quartz and the fluorite is not large enough to correct chromatic aberration. For this reason, if the exposure wavelength becomes 300 nm or less, and a projection optical system is constituted by only a refracting optical system, chromatic aberration correction is very difficult to perform. In addition, since fluorite undergoes a considerable change in refractive index with a change in temperature, i.e., has poor temperature characteristics, and involves many problems in a lens polishing process, fluorite cannot be used for many portions. It is, therefore, very difficult to form a projection optical system having a required solution by using only a refracting system.

In contrast to this, attempts have been made to form a projection optical system by using only a reflecting system. In this case, however, the projection optical system increases in size and requires aspherical reflecting surfaces. It is very difficult to manufacture large, high-precision, aspherical surfaces

Under the circumstances, various techniques have been proposed to form a reduction projection optical system by using a so-called catadioptric optical system constituted by a combination of a reflecting system and a refracting system consisting of optical glass usable in relating to the exposure wavelength to be used. As an example, a reduction projection exposure apparatus including a catadioptric projection optical system having a beam splitter constituted by a cubic prism and serving to project a reticle image entirely by using a light beam near the optical axis is disclosed in, e.g., U.S. Pat. Nos. 4,953,960, 5,220,454, 5,089,913, or 5,402,267.

SUMMARY OF THE INVENTION

The present invention has as its object to provide a catadioptric reduction projection optical system which can use a beam splitting optical system smaller in size than a conventional polarizing beam splitter, can set a long optical path from a concave reflecting mirror to the image plane, can easily adjust the optical system, and has excellent imaging performance.

It is another object of the present invention to provide a catadioptric reduction projection optical system which can reduce the size of a beam splitting optical system such as a polarizing beam splitter and still has a space in which an aperture stop can be arranged.

It is still another object of the present invention to provide a catadioptric reduction projection optical system which uses a compact beam splitting optical system and can be applied to a projection optical apparatus of the scanning exposure scheme.

The catadioptric reduction projection optical system can be applied to a projection exposure apparatus of a scanning exposure method, based on use of a compact beam splitting means such as a polarizing beam splitter and the like. Besides a projection exposure apparatus of a one-shot exposure method, the catadioptric reduction projection optical system can be also applied to a recent apparatus employing a scanning exposure method such as the slit scan method or the step-and-scan method, etc. for effecting exposure while relatively scanning a reticle and a wafer to a projection optical system.

To achieve the above objects, as shown in FIGS. 1 and 2, an projection exposure apparatus of the present invention comprises at least a wafer stage 3 being movable and allowing photosensitive substrate W to be held on a main surface thereof, an illumination optical system 1 for emitting exposure light of a predetermined wavelength and transferring a predetermined pattern of a mask (reticle R) onto the substrate W, and a catadioptric reduction projection optical system 5 provided between a first surface P1 on which the mask R is disposed and a second surface P2 on which a surface of the substrate W is corresponded, for projecting an image of the pattern of the mask R onto the substrate W. The illumination optical system 1 includes an alignment optical system 110 for adjusting a relative positions between the mask R and the substrate W, and the mask R is disposed on a reticle stage 2 which is movable in parallel with respect to the main surface of the wafer stage 3. The catadioptric reduction projection optical system has a space permitting an aperture stop 6 to be set therein. The sensitive substrate W comprises a wafer 8 such as a silicon wafer or a glass plate, etc., and a photosensitive material 7 such as a photoresist and the like coating a surface of the wafer 8.

In particular, the catadioptric reduction projection optical system, as shown in FIGS. 3 and 4, includes at least a first imaging optical system having a focal length f_1 (refracting lens group $G_1(f_1)$) having a positive refractive power and for forming a first intermediate image 9 as a reduced image of the pattern on the object plane P1, beam splitting means 10 for splitting at least part of a light beam from the first imaging optical system, a second imaging optical system having a focal length f_2 (catadioptric lens group $G_2(f_2)$) including a concave reflecting mirror M_1 for reflecting a light beam split by the beam splitting means, and for forming a second intermediate image 12 as an image of the

first intermediate image 9, and a third imaging optical system having a focal length f_3 (refracting lens group $G_3(f_3)$) for forming a third intermediate image (a final image) as an image of the second intermediate image 12 on the image plane P2 on the basis of a light beam, of a light beam from the second imaging optical system, which is split by the beam splitting means 10.

Since the first imaging optical system $G_1(f_1)$ forms a first reduced intermediate image in an optical path from the image plane P1 to the concave reflecting mirror M_1 (or M_2), the beam splitting means can exactly carry out the splitting of a light beam from the first imaging optical system $G_1(f_1)$. Since the second imaging optical system $G_2(f_2)$ forms a second intermediate image in an optical path from the concave reflecting mirror M_1 (or M_2) to the third imaging optical system $G_3(f_3)$, a smaller beam splitting means can be used in the catadioptric reduction optical system of the present invention. Additionally, as shown in FIGS. 3 and 4, the second imaging optical system $G_2(f_2)$ can be used the concave reflecting mirror M_1 so that the mirror M_1 sandwiches the beam splitter 10 with the first imaging optical system $G_1(f_1)$ and, also can be used the concave reflecting mirror M_2 so that the mirror M_2 sandwiches the beam splitter 10 with the third imaging optical system $G_3(f_3)$.

If the beam splitting means is a prism type beam splitter 10, at least one of the first and second intermediate images 9, 12 is preferably formed in the prism type beam splitter.

If the beam splitting means is a partial reflecting mirror 13 for partially reflecting a light beam from the first imaging optical system (refracting lens group $G_1(f_1)$) as shown in FIG. 5, the second intermediate image 12 is preferably formed in an optical path form the first imaging optical system to the concave reflecting mirror M_1 of the second imaging optical system and is located at the concave reflecting mirror side of the partial reflecting mirror 13. In other words, the intermediate image 12 is formed between the concave reflecting mirror M_1 and the partial reflecting mirror 13.

In addition, the following inequalities are preferably satisfied:

$$p_1+p_3>0 \quad (1)$$

$$p_2<0 \quad (2)$$

$$|p_1+p_2+p_3|\leq 0.1 \quad (3)$$

where p_1, p_2, and p_3 are the Petzval sums of the first imaging optical system (refracting lens group $G_1(f_1)$), the second imaging optical system (catadioptric lens group $G_2(f_2)$), and the third imaging optical system (refracting lens group $G_3(f_3)$), respectively.

Furthermore, the following relations are preferably satisfied:

$$0.1\leq|\beta_1|\leq 1 \quad (4)$$

$$0.5\leq|\beta_2|\leq 2 \quad (5)$$

$$0.25\leq|\beta_3|\leq 1.5 \quad (6)$$

$$|\beta_1\cdot\beta_2\cdot\beta_3|\leq 1 \quad (7)$$

where β_1 is the magnification between the pattern of the first surface and the first intermediate image, β_2 is the magnification between the first intermediate image and the second intermediate image, and β_3 is the magnification between the second intermediate image and the third intermediate image.

According to the catadioptric reduction projection optical system of the present invention, when the polarizing beam

splitter 10 (PBS) is used as a beam splitting means as shown in FIGS. 3 and 4, the system is suitable for the one-shot exposure method even though the system can be applied to the scanning exposure method. In this case, a light beam incident on the second imaging optical system (catadioptric lens group $G_2(f_2)$) and a light beam reflected thereby are split by the polarizing beam splitter 10 to be guided to the subsequent optical system. In addition, the polarizing beam splitter 10 is arranged near the position where the light beam is focused as the second intermediate image 12 after the first intermediate image 9 is formed, i.e., the portion where the light beams is intensively focused. Therefore, the polarizing beam splitter 10 can be reduced in size. In addition, the blanket wafer exposure scheme can be employed unlike a so-called ring field optical system for exposing only an annular zone by using an off-axis beam.

In addition, by using a light beam from the second intermediate image 12, an image can be formed again on the second surface P2 by the third imaging optical system (refracting lens group $G_3(f_3)$). For this reason, the working distance from, e.g., a wafer placed on the second surface to the third imaging optical system ($G_3(f_3)$) can be set to be long. In addition, since an aperture stop 6 can be easily arranged in the third imaging optical system ($G_3(f_3)$), the coherent factor (σ value) as the ratio between the numerical aperture of the illumination optical system and that of the projection optical system can be controlled in a wide range, thereby controlling the imaging characteristics.

Theoretically, the number of lenses of the third imaging optical system ($G_3(f_3)$) can be increased infinitely. For this reason, the numerical aperture (NA) of the projection optical system can be increased. That is, a bright optical system can be obtained.

In a general reflecting optical system, an optical path must always be deflected at a given position in the optical system. The precision in decentering the optical axis at the deflected portion is strict, posing serious problems in the manufacture of the optical system. In the present invention, however, if, for example, the optical path of a light beam from the second imaging optical system ($G_2(f_2)$) is deflected by the polarizing beam splitter 10, decentering of an optical system constituted by the first and second imaging optical systems ($G_1(f_1)$, $G_2(f_2)$) and decentering of the third imaging optical system (G_3) can be independently adjusted. Thereafter, a structure for combining the two optical systems at a right angle can be employed. Therefore, decentering adjustment and the like are theoretically facilitated.

With regard to this point, according to the present invention, since the polarizing beam splitter 10 is arranged near the first intermediate image 9 or the second intermediate image 12 having a relatively low decentering sensitivity, even if decentering occurs in deflecting the optical path, the influence of this decentering on the optical performance is small.

In addition, as shown in FIGS. 3 and 4, even if, for example, a wafer w is horizontally placed on the second surface P2, since, for example, a reticle on the first surface P1 and the first imaging optical system ($G_1(f_1)$) can be horizontally arranged, the overall projection optical system can be set to be lower in height than a conventional projection optical system constituted by a refracting lens system. That is, the vertical dimension can be reduced. In other words, since there is a good vertical dimension margin, the optical system can be arranged with a good margin.

In order to reduce the light amount loss in the polarizing beam splitter 10, it is preferable that a prism type beam splitter 10 be used as a polarizing beam splitter, and a λ/4

catadioptric projection optical system, for example, a maximum field angle of about 20° or more is required to split the optical path. In contrast to this, a light beam incident on the mirror in the present invention exhibits a field angle of about 10°, and hence aberration correction is facilitated.

A so-called ring field optical system is known as a projection optical system for the scanning exposure method, and the ring field optical system is constructed to illuminate only an off-axis annular portion. It is, however, difficult for the ring field optical system to have a large numerical aperture, because it uses an off-axis beam. Further, because optical members in that system are not symmetric with respect to the optical axis, processing, inspection, and adjustment of the optical members are difficult, and accuracy control or accuracy maintenance is also difficult. In contrast with it, because the angle of view is not large in the present invention, the optical system is constructed in a structure with less eclipse of beam.

In the present invention, in order to improve the performance of an optical system, the Petzval sum of the overall optical system must be set to be near 0. For this purpose, inequalities (1) to (3) above are preferably satisfied.

By satisfying inequalities (1) to (3) above, the curvature of field, which is associated with the optical performance, is suppressed to improve the flatness of the image plane. The image plane is curved toward the object plane P1 in a concave form beyond the upper limit of inequality (3) ($p_1+p_2+p_3\geq 0.1$), and is curved toward the object plane P1 in a convex form below the lower limit of inequality (3) ($p_1+p_2+p_3\leq -0.1$). As a result, the imaging performance considerably deteriorates.

When part of an off-axis imaging light beam is to be used, i.e., ring field illumination is to be performed, the Petzval

illustration only, since various changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art from this detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a structural drawing to show an exposure apparatus of a one-shot exposure method;

FIG. 2 is a structural drawing to show an exposure apparatus of a scanning exposure method;

FIG. 3 is an optical path diagram showing the schematic arrangement of a catadioptric reduction projection optical system according to the first embodiment of the present invention;

FIG. 4 is an optical path diagram showing a modification of the first embodiment;

FIGS. 5 to 7 are views showing the schematic arrangement, the exposure field, and the like of the second embodiment of the present invention;

FIGS. 8 to 10 are views showing the schematic arrangement, the exposure field, and the like of the third embodiment of the present invention;

FIG. 11 is an optical path diagram showing a projection optical system according to the first embodiment of the present invention;

FIGS. 12 to 15 and 16(a) to 16(c) are aberration charts in the first embodiment of FIG. 11;

FIG. 17 is an optical path diagram showing a projection optical system according to the second embodiment of the present invention;

FIGS. 18 to 21 and 22(a) to 22(c) are aberration charts in the second embodiment of FIG. 17;

FIG. 23 is an optical path diagram showing a projection optical system according to the third embodiment of the present invention;

FIGS. 24 to 26 and 27(*a*) to 27(*d*) are aberration charts in the third embodiment of FIG. 23; and

FIG. 28 shows a schematic structure of an exposure apparatus of a one-shot method using a catadioptric reduction projection optical system according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Various embodiments of the catadioptric reduction projection optical system according to the present invention will be described with reference to the drawings. In the examples, the optical system is applied to the projection optical system in the projection exposure apparatus for projecting a reduced image of patterns of reticle onto a wafer coated by a photoresist, using a one-shot exposure method or a scanning exposure method. FIG. 1 shows a basic structure of the exposure apparatus using a one-shot exposure method. As shown in FIG. 1, an exposure apparatus comprises at least a movable wafer-stage 3 allowing a photosensitive substrate W to be held on a main surface 3*a* thereof, an illumination optical system 1 for emitting exposure light of a predetermined wavelength and transferring a predetermined pattern of a mask (reticle R) onto the substrate W, a light source 100 for supplying an exposure light to the illumination optical system 1, a catadioptric reduction projection optical system 5 provided between a first surface P1 (object plane) on which the mask R is disposed and a second surface P2 (image plane) to which a surface of the substrate W is corresponded, for projecting an image of the pattern of the mask R onto the substrate W. The illumination optical system 1 includes an alignment optical system 110 for adjusting a relative positions between the mask R and the wafer W, and the mask R is disposed on a reticle stage 2 which is movable in parallel with respect to the main surface of the wafer stage 3. A reticle exchange system 200 conveys and changes a reticle (mask R) to be set on the reticle stage 2. The reticle exchange system 200 includes a stage driver for moving the reticle stage 2 in parallel with respect to the main surface 3*a* of the wafer stage 3. The catadioptric reduction projection optical system 5 has a space permitting an aperture stop 6 to be set therein. The sensitive substrate W comprises a wafer 8 such as a silicon wafer or a glass plate, etc., and a photosensitive material 7 such as a photoresist or the like coating a surface of the wafer 8. The wafer stage 3 is moved in parallel with respect to a object plane P1 by a stage control system 300. Further, since a main control section 400 such as a computer system controls the light source 100, the reticle exchange system 200, the stage control system 300 or the like, the exposure apparatus can perform a harmonious action as a whole.

FIG. 2 shows the basic structure of an exposure apparatus using a scanning exposure method. In FIG. 2, the exposure apparatus also comprises a wafer stage 3, a reticle stage 2, an illumination optical system 1, and a catadioptric reduction projection optical system 5. The illumination optical system 1 emits a light beam from the light source 100 to an illumination region on the reticle R, the illumination region being a predetermined shaped. The catadioptric reduction projection optical system 5 projects a reduced image of a pattern of the region on the reticle R to an exposure region on the wafer W (photosensitive substrate). The reticle stage control system 210 can move the reticle stage 2 with respect to the surface P2 of the wafer W and is included in the reticle exchange system 200. The main control section 400 such as a computer system controls the light source 100, the reticle exchange system 200. In particular, the main control section 400 separately controls the reticle stage control system 210 and the wafer stage control system 300 and, thereby can perform a scanning exposure method with changing a relative position between an illumination region on the reticle R and an exposure region on the wafer W.

The techniques relating to an exposure apparatus of the present invention are described, for example, in U.S. patent applications Ser. No. 255,927, No. 260,398, No. 299,305, U.S. Pat. No. 4,497,015, No. 4,666,273, No. 5,194,893, No. 5,253,110, No. 5,333,035, No. 5,365,051, No. 5,379,091, or the like. The reference of U.S. patent application Ser. No. 255,927 teaches an illumination optical system (using a laser source) applied to a scan type exposure apparatus. The reference of U.S. patent application Ser. No. 260,398 teaches an illumination optical system (using a lamp source) applied to a scan type exposure apparatus. The reference of U.S. patent application Ser. No. 299,305 teaches an alignment optical system applied to a scan type exposure apparatus. The reference of U.S. Pat. No. 4,497,015 teaches an illumination optical system (using a lamp source) applied to a scan type exposure apparatus. The reference of U.S. Pat. No. 4,666,273 teaches a step-and repeat type exposure apparatus capable of using the catadioptric projection optical system of the present invention. The reference of U.S. Pat. No. 5,194,893 teaches an illumination optical system, an illumination region, mask-side and reticle-side interferometers, a focusing optical system, alignment optical system, or the like. The reference of U.S. Pat. No. 5,253,110 teaches an illumination optical system (using a laser source) applied to a step-and-repeat type exposure apparatus. The '110 reference can be applied to a scan type exposure apparatus. The reference of U.S. Pat. No. 5,333,035 teaches an application of an illumination optical system applied to an exposure apparatus. The reference of U. S. Pat. No. 5,365,051 teaches a auto-focusing system applied to an exposure apparatus. The reference of U.S. Pat. No. 5,379,091 teaches an illumination optical system (using a laser source) applied to a scan type exposure apparatus.

Next, as described above, the optical system is applied to projection exposure apparatuses of a one-shot exposure method and a scanning exposure method, which are designed to project an image of a pattern on a reticle onto a wafer coated with a photoresist at a predetermined magnification.

With regard to the lens arrangement in each of the following embodiments, for example, as shown in FIG. 11, flat virtual planes (e.g., a plane r_{20}) are respectively used as the reflecting surface (r_{30}) and mirror surface of a concave reflecting mirror M_1. In order to express the shapes of lenses and the distances therebetween, the pattern surface of a reticle R is assumed to be the 0th plane, and each of the planes through which light emerging from the reticle R passes-until it reaches a wafer W is sequentially assumed to be the ith plane (i=1, 2, . . .), whereas the positive sign of the radius of curvature, r_i, of the ith plane indicates a convex lens with respect to a light beam from the reticle R. In addition, the plane distance between the ith plane and the (i+1)th plane is represented by d_i. SiO_2 represents fused quartz as a glass material. The fused quartz has the following refractive index with respect to the used reference wavelength (193 nm):

refractive index of fused quartz: 1.5610

First Embodiment

The first embodiment is a projection optical system suitable for a projection optical apparatus (e.g., a stepper) of a one-shot exposure method and having a magnification of 1/4x.

FIGS. 3 and 4 show the overall arrangement of the first embodiment. Referring to FIGS. 3 and 4, a reticle R (see FIG. 11) on which a pattern to be transferred is drawn is placed on an object plane P1, and a wafer W (see FIG. 11) coated with a photoresist is placed on an image plane P2. The reticle R on the object plane P1 is illuminated with exposure illumination light from the light source 100 of the illumination optical system 1, and a light beam passing through the reticle R forms a first intermediate image 9 via a refracting lens group G_1 as a focusing lens group having a focal length f_1. A light beam from the first intermediate image 9 is incident on a polarizing beam splitter (PBS) 10. A p-polarized light beam transmitted through a polarizing/reflecting surface 10a of the polarizing beam splitter 10 passes through λ/4 plate 11 and is reflected by a catadioptric lens group G_2, having a focal length f_2 and including a concave reflecting mirror M_2. Thereafter, the light beam returns as an s-polarized light beam to the polarizing beam splitter 10 via the λ/4 plate 11 to form a second intermediate image 12 in the polarizing beam splitter 10. Note that the catadioptric lens group $G_2(f_2)$ includes a refracting lens in practice, as shown in FIG. 11.

Most of the s-polarized light beam from the second intermediate image 12 is reflected by the polarizing/reflecting surface 10a to form a reduced image of the reticle pattern onto the wafer W on the image plane P1 via a refracting lens group G_3 as a focusing lens group having a Focal length f_3. In addition, an aperture stop 6a is arranged near the pupil plane of the refracting lens group $G_1(f_1)$ along an optical axis AX_1 of the refracting lens group $G_1(f_1)$, and an aperture stop 6b is arranged near the pupil plane of the refracting lens group $G_3(f_3)$ along an optical axis AX_3 of the refracting lens group $G_3(f_3)$.

In this embodiment, since the second intermediate image 12 is formed to be closer to the concave reflecting mirror M_2 than the polarizing/reflecting surface 10a, the polarizing beam splitter 10, in particular, can be reduced in size.

FIG. 11 shows the detailed lens arrangement in the first embodiment of FIG. 3 (FIG. 4). The λ/4 plate 11 in FIG. 3 is omitted from the arrangement shown in FIG. 11.

As shown in FIG. 11, the refracting lens group $G_1(f_1)$ is constituted by in the following order from the reticle side: a negative meniscus lens L_{11} having a convex surface facing the reticle R, a negative meniscus lens L_{12} having a concave surface facing the reticle R, a biconvex lens (to be simply referred to as a convex lens hereinafter) L_{13}, a convex lens L_{14}, a negative meniscus lens L_{15} having a convex surface facing the reticle R, a negative meniscus lens L_{16} having a concave surface facing the reticle R, a convex lens L_{17}, a convex lens L_{18}, a convex lens L_{19}, a biconcave lens (to be simply referred to as a concave lens hereinafter) L_{1A}, a convex lens L_{1B}, and a convex lens L_{1C}. The catadioptric lens group $G_2(f_2)$ is constituted by a negative meniscus lens L_{20} having a concave surface facing the reticle R and the concave reflecting mirror M_2.

The refracting lens group $G_3(f_3)$ is constituted by a convex lens L_{31}, a positive meniscus lens L_{32} having a convex surface facing the reticle R (polarizing beam splitter 10), a negative meniscus lens L_{33} having a convex surface facing the reticle R, a convex lens L_{34}, a convex lens L_{35}, a convex lens L_{36}, a negative meniscus lens L_{37} having a concave surface facing the reticle R, a negative meniscus lens L_{38} having a concave surface facing the reticle R, a positive meniscus lens L_{39} having a concave surface facing the reticle R, a negative meniscus lens L_{3A} having a concave surface facing the reticle R, a convex lens L_{3B}, a negative meniscus lens L_{3C} having a convex surface facing the reticle R, a positive meniscus lens L_{3D} having a convex surface facing the reticle R, and a negative meniscus lens L_{3E} having a convex surface facing the reticle R.

The aperture stop 6a is arranged at the Fourier transform plane in the refracting lens group $G_1(f_1)$, i.e., between the convex lens L_{17} and the convex lens L_{18}. The aperture stop 6b is arranged at the Fourier transform plane in the refracting lens group $G_3(f_3)$, i.e., near the reticle-side surface of the negative meniscus lens L_{37}.

The reduction ratio of the overall system is 1/4x, the numerical aperture (NA) on the wafer side (image side) is 0.5, and the object height is 60 mm.

One type of optical glass consisting of fused quartz is used for all the refracting lenses. The system is corrected for axial chromatic aberration and for chromatic aberration of magnification with respect to a wavelength width of 1 nm in the wavelength (193 nm) of an ultraviolet excimer laser beam. In addition, spherical aberration, coma, astigmatism, and distortion are corrected to attain an almost aberration-free state, thereby realizing an optical system having excellent imaging performance.

The curvature radii r_i, plane distances d_i, and glass materials used in the first embodiment shown in FIG. 11 are shown in Table 1. In Table 1, the 29th and 34th planes are virtual planes indicating the polarizing/reflecting surfaces of the concave reflecting mirror M_2 and the polarizing beam splitter 10.

TABLE 1

i	r_i	d_i	Glass Material	i	r_i	d_i	Glass Material
0	—	34.6		33	∞	41.2	SiO_2
1	107.95	30.0	SiO_2	34	∞	0.0	
2	93.49	60.0		35	∞	41.2	SiO_2
3	−64.39	30.0	SiO_2	36	∞	7.1	
4	−80.34	31.2		37	412.21	18.0	SiO_2
5	1879.66	42.0	SiO_2	38	−151.48	3.0	
6	−234.73	7.2		39	50.81	24.0	SiO_2
7	1132.81	30.0	SiO_2	40	422.76	7.2	
8	−209.18	6.0		41	1244.69	9.0	SiO_2
9	655.92	13.5	SiO_2	42	90.94	12.0	
10	129.99	37.5		43	753.18	19.2	SiO_2
11	−80.54	12.0	SiO_2	44	−187.50	29.7	
12	−161.37	9.0		45	318.30	18.0	SiO_2
13	232.17	36.0	SiO_2	46	−383.26	3.0	
14	−235.30	186.0		47	167.48	18.0	SiO_2
15	999.87	27.0	SiO_2	48	−2492.32	27.3	
16	−175.63	3.0		49	−113.03	16.8	SiO_2
17	203.15	18.0	SiO_2	50	−139.99	36.6	
18	−3006.49	21.3		51	−125.26	24.6	SiO_2
19	−94.09	18.0	SiO_2	52	−135.38	1.5	
20	287.07	30.6		53	−454.54	24.6	SiO_2
21	7834.30	33.0	SiO_2	54	−142.46	9.0	
22	−111.27	3.0		55	−82.96	18.0	SiO_2
23	−103.80	30.0	SiO_2	56	−107.78	1.5	
24	−6760.25	78.5		57	394.38	30.0	SiO_2
25	∞	82.5	SiO_2	58	−157.74	1.5	
26	∞	162.3		59	63.96	17.1	SiO_2
27	−76.86	7.5	SiO_2	60	47.02	3.0	
28	−189.23	10.5		61	47.29	30.0	SiO_2
29	∞	0.0		62	151.47	1.5	
20	126.03	10.5		63	55.43	11.4	SiO_2
31	189.23	7.5	SiO_2	64	47.29	19.9	
32	76.86	162.3					

FIGS. 12 to 14 respectively show longitudinal aberration charts in the first embodiment; FIG. 12 shows a spherical

aberration of this embodiment; FIG. 13 shows an astigmatism of this embodiment; and FIG. 14 shows a distortion of this embodiment. Further, FIG. 15 shows a magnification chromatic aberration chart in the first embodiment. FIGS. 16(*a*), 16(*b*) and 16(*c*) show transverse aberration charts in the first embodiment. In these aberration charts, reference symbols J, P, and Q respectively denote characteristic curves at the used reference wavelength (193 nm), 192.5 nm, and 193.5 nm.

The height of the projection optical system of this embodiment is mainly determined by the refracting lens group $G_3(f_3)$. The height of the refracting lens group $G_3(f_3)$ is about 600 mm at most. That is, the height of this system is about 1/2 that of a projection optical system constituted by a conventional refracting system.

In this embodiment, as shown in FIG. 3, of the light from the refracting lens group $G_1(f_1)$, a light beam which is transmitted through the polarizing beam splitter 10 is guided to the catadioptric lens group $G_2(f_2)$. As shown in FIG. 4, however, of the light from the refracting lens group $G_2(f_2)$, a light beam which is reflected by the polarizing beam splitter 10 may be guided to the catadioptric lens group $G_2(f_2)$ via the $\lambda/4$ plate 11. In this case, the light beam reflected by the concave reflecting mirror M_2 in the catadioptric lens group $G_2(f_2)$ is converted into a p-polarized light beam by the $\lambda/4$ plate 11 to form the second intermediate image 12 in the polarizing beam splitter 10. After most of the light beam from the second intermediate image 12 is transmitted through the polarizing/reflecting surface 10*a*, the light forms a reticle pattern image on the wafer W via the refracting lens group $G_3(f_3)$.

Second Embodiment

The second embodiment is a projection optical system suitable for a projection optical apparatus based on the scanning exposure scheme and having a magnification of 1/4x.

FIG. 5 shows the overall arrangement of the second embodiment. Referring to FIG. 5, a reticle R is placed on an object plane P1, and a wafer W is placed on an image plane P2. FIG. 6 is a plane view showing the reticle R when viewed in the direction of a refracting lens group $G_1(f_1)$ in FIG. 5. In this case, a bar-shaped illumination region 22, on the reticle R, which is slightly offset from the optical axis of the projection optical system is illuminated with illumination light from the light source 100 of the illumination optical system 1.

Referring to FIG. 5, a light beam passing through the illumination region 22 forms a first intermediate image 9 via the refracting lens group G_1, and a light beam from the first intermediate image 9 passes through a side surface of a mirror (to be referred to as a partial mirror hereinafter) 13 set at an angle of almost 45° with respect to an optical axis AX_1 to cover the lower half portion of the optical axis AX_1. The light beam is then reflected by a catadioptric lens group $G_2(f_2)$ including a concave reflecting mirror M_1 to form a second intermediate image 12 in front of the partial mirror 13. Note that the catadioptric lens group $G_2(f_2)$ includes a refracting lens in practice, as shown in FIG. 17.

A light beam from the second intermediate image 12 is reflected by the partial mirror 13 to form a reduced image of a reticle pattern on the wafer W on the image plane P2 via a refracting lens group $G_3(f_3)$. In addition, an aperture stop 6*a* is arranged near the pupil plane of the refracting lens group $G_1(f_1)$, and an aperture stop 6*b* is arranged near the pupil plane of the refracting lens group $G_3(f_3)$.

FIG. 7 is a plan view of the wafer W in FIG. 5. As shown in FIG. 5, the reduced image of the reticle pattern is projected onto a bar-shaped exposure region 24, on the wafer W, which is slightly offset from an optical axis AX_3. Therefore, in order to expose the pattern on the entire surface of the reticle R, the wafer W may be scanned to the right (or the left) at a velocity V_W $(-\beta \cdot V_R)$ in synchronism with the downward (upward) scanning of the reticle R at a velocity V_R in FIG. 5, provided that the magnification of the overall system is represented by β.

In this embodiment, since the second intermediate image 12 is formed at the concave reflecting mirror side of the partial mirror 13 and is located between the concave reflecting mirror M_1 and the partial mirror 13, the projection optical system can be reduced in size in the vertical direction in particular.

FIG. 17 shows the detailed lens arrangement in the second embodiment.

As shown in FIG. 17, the refracting lens group $G_1(f_1)$ is constituted by in the following order from the reticle side: a positive meniscus lens L_{11} having a convex surface facing the reticle R, a negative meniscus lens L_{12} having a convex surface facing the reticle R, a negative meniscus lens L_{13} having a concave surface facing the reticle R, a positive meniscus lens L_{14} having a concave surface facing the reticle R, a convex lens L_{15}, a positive meniscus lens L_{16} having a concave surface facing the reticle R, a negative meniscus lens L_{17} having a convex surface facing the reticle R, a negative meniscus lens L_{18} having a concave surface facing the reticle R, a convex lens L_{19}, a positive meniscus lens L_{1A} having a concave surface facing the reticle R, a positive meniscus lens L_{1B} having a concave surface facing the reticle R, a convex lens L_{1C}, a negative meniscus lens L_{1D} having a concave surface facing the reticle R, a positive meniscus lens L_{1E} having a concave surface facing the reticle R, and a positive meniscus lens L_{1F} having a convex surface facing the reticle R. The catadioptric lens group $G_2(f_2)$ is constituted by a negative meniscus lens L_{20} having a concave surface facing the reticle R and the concave reflecting mirror M_1.

A refracting lens group $G_3(f_3)$ is constituted by a convex lens L_{31}, a convex lens L_{32}, a negative meniscus lens L_{33} having a convex surface facing the reticle R (partial mirror 13), a positive meniscus lens L_{34} having a concave surface facing the reticle R, a convex lens L_{35}, a positive meniscus lens L_{36} having a convex surface facing the reticle R, a negative meniscus lens L_{37} having a concave surface facing the reticle R, a positive meniscus lens L_{38} having a concave surface facing the reticle R, a negative meniscus lens L_{39} having a concave surface facing the reticle R, a convex lens L_{3A}, a negative meniscus lens L_{3B} having a convex surface facing the reticle R, a positive meniscus lens L_{3C} having a convex surface facing the reticle R, and a negative meniscus lens L_{3D} having a convex surface facing the reticle R. The aperture stop 6*a* is arranged near the Fourier transform plane in the refracting lens group $G_1(f_1)$, i.e., at a plane near the positive meniscus lens L_{1B} on the reticle R. The aperture stop 6*b* is arranged near the Fourier transform plane in the refracting lens group $G_3(f_3)$, i.e., a plane near the positive meniscus lens L_{34} on the reticle R.

The reduction ratio of the overall system is 1/4x, the numerical aperture (NA) on the wafer W side (image side) is 0.45, and the object height is 60 mm.

One type of optical glass consisting of fused quartz is used for all the refracting lenses. The system is corrected for axial chromatic aberration and for chromatic aberration of magnification with respect to a wavelength width of 1 nm in the wavelength (193 nm) of an ultraviolet excimer laser beam. In addition, spherical aberration, coma, astigmatism, and

distortion are corrected to attain an almost aberration-free state, thereby realizing an optical system having excellent imaging performance.

The curvature radii r_i, plane distances d_i, and glass materials used in the second embodiment shown in FIG. 17 are shown in Table 2. In Table 2, the 34th plane is a virtual plane indicating the reflecting surfaces of the concave reflecting mirror M_1.

TABLE 2

i	r_i	d_i	Glass Material	i	r_i	d_i	Glass Material
0	—	33.7		33	−200.63	5.1	
1	115.59	24.0	SiO_2	34	∞	0.0	
2	206.01	3.0		35	124.83	5.1	
3	82.73	15.0	SiO_2	36	200.63	8.5	SiO_2
4	64.61	51.0		37	78.74	195.8	
5	−65.23	6.0	SiO_2	38	∞	30.0	
6	−487.74	6.0		39	4302.84	18.0	SiO_2
7	−187.92	36.0	SiO_2	40	−160.56	3.0	
8	−85.94	24.0		41	111.38	18.0	SiO_2
9	256.51	42.0	SiO_2	42	−1676.43	3.0	
10	−210.33	7.0		43	977.92	21.0	SiO_2
11	−296.05	30.0	SiO_2	44	102.28	12.0	
12	−182.85	6.0		45	−988.64	28.2	SiO_2
13	176.46	13.4	SiO_2	46	−117.27	30.4	
14	87.59	36.0		47	251.58	18.0	SiO_2
15	−72.74	18.0	SiO_2	48	−301.71	3.0	
16	−182.58	3.0		49	186.32	18.0	SiO_2
17	292.35	36.1	SiO_2	50	730.15	27.0	
18	−177.49	17.6		51	−205.32	16.8	SiO_2
19	−204.01	30.0	SiO_2	52	−482.46	60.5	
20	−157.05	87.0		53	−481.92	24.7	SiO_2
21	−277.13	27.0	SiO_2	54	−142.39	9.0	
22	−161.85	64.8		55	−92.11	20.2	SiO_2
23	318.99	24.0	SiO_2	56	−133.33	1.5	
24	−732.51	26.8		57	207.89	24.0	SiO_2
25	−115.97	18.0	SiO_2	58	−204.01	1.5	
26	−335.19	12.0		59	60.36	17.1	SiO_2
27	−827.23	33.0	SiO_2	60	49.08	9.0	
28	−159.61	3.0		61	55.94	27.0	SiO_2
29	93.92	24.0	SiO_2	62	420.19	1.5	
30	1239.44	105.0		63	39.71	11.2	SiO_2
31	∞	195.8		64	36.46	11.0	
32	−78.74	8.5	SiO_2				

FIGS. 18 to 20 respectively are longitudinal aberration charts in the second embodiment; FIG. 18 shows a spherical aberration of this embodiment; FIG. 19 shows an astigmatism of this embodiment; and FIG. 20 shows a distortion. Further, FIG. 21 shows a magnification chromatic aberration chart in the second embodiment. FIGS. 22(*a*), 22(*b*) and 22(*c*) show transverse aberration charts in the second embodiment.

Although the second embodiment exemplifies the scanning exposure apparatus, the present invention can be applied to a projection exposure apparatus of a one-shot exposure method.

Third Embodiment

The third embodiment is a projection optical system suitable for a projection exposure apparatus of a scanning exposure method and having a magnification of 1/4×. A partial mirror is used in the third embodiment like in the second embodiment. However, an off-axis light ray further offset from the optical axis than in the second embodiment is used in the third embodiment.

FIG. 8 shows the overall arrangement of the second embodiment. Referring to FIG. 8 which indicates similar or same parts with the same reference numerals as in FIG. 5, a reticle 21 is placed on an object plane P1, and a wafer W is placed on an image plane P2. FIG. 9 is a plane view showing the reticle R when viewed in the direction of a refracting lens group $G_1(f_1)$. As shown in FIG. 9, an arcuated illumination region 22A, on the reticle R, which is slightly offset from the optical axis of the projection optical system is illuminated.

Referring to FIG. 8, a light beam passing through the illumination region 22A forms a reduced image of a reticle pattern on an exposure region 24A (see FIG. 10) on the wafer W through the refracting lens group $G_1(f_1)$, a catadioptric lens group $G_2(f_2)$ including a concave reflecting mirror M_1, a partial mirror 13, and a refracting lens group $G_3(f_3)$. In this case, in order to expose the pattern on the entire surface of the reticle R onto the wafer W, the wafer W may be scanned to the right (or the left) in synchronism with the downward (or upward) scanning of the reticle R in FIG. 9.

In this embodiment, a second intermediate image 12 is formed at the reflecting lens group side of the partial mirror 13 and is located between the refracting lens group $G_3(f_3)$ and the mirror 13.

FIG. 23 shows the detailed lens arrangement in the third embodiment.

As shown in FIG. 23, the refracting lens group $G_1(f_1)$ is constituted by in the following order from the reticle side: a positive meniscus lens L_{11} having a convex surface facing the reticle R, a negative meniscus lens L_{12} having a convex surface facing the reticle R, a negative meniscus lens L_{13} having a concave surface facing the reticle R, a positive meniscus lens L_{14} having a concave surface facing the reticle R, a convex lens L_{15}, a negative meniscus lens L_{16} having a concave surface facing the reticle R, a negative meniscus lens L_{17} having a convex surface facing the reticle R, a negative meniscus lens L_{18} having a concave surface facing the reticle R, a convex lens L_{19}, a positive meniscus lens L_{1A} having a concave surface facing the reticle R, a positive meniscus lens L_{1B} having a concave surface facing the reticle R, a convex lens L_{1C}, a negative meniscus lens L_{1D} having a concave surface facing the reticle R, a negative meniscus lens L_{1E} having a concave surface facing the reticle R, and a positive meniscus lens L_{1F} having a convex surface facing the reticle R. The catadioptric lens group $G_2(f_2)$ is constituted by a negative meniscus lens L_{2n} having a concave surface facing the reticle R and the concave reflecting mirror M_1.

A refracting lens group $G_3(f_3)$ is constituted by a positive meniscus lens L_{31} having a concave surface facing the reticle side (partial mirror 13), a convex lens L_{32}, a concave lens L_{33}, a positive meniscus lens L_{34} having a concave surface facing the reticle R, a convex lens L_{35}, a positive meniscus lens L_{36} having a convex surface facing the reticle R, a negative meniscus lens L_{37} having a concave surface facing the reticle R, a positive meniscus lens L_{38} having a concave surface facing the reticle R, a negative meniscus lens L_{39} having a concave surface facing the reticle R, a positive meniscus lens L_{3A} having a convex surface facing the reticle R, a convex lens L_{3B}, a positive meniscus lens L_{3C} having a convex surface facing the reticle R, and a negative meniscus lens L_{3D} having a convex surface facing the reticle R. An aperture stop 6*a* is arranged near the Fourier transform plane in the refracting lens group $G_1(f_1)$, i.e., between the positive meniscus lens L_{1B} and the convex lens L_{1C}. A portion near the Fourier transform plane in the refracting lens group $G_3(f_3)$, i.e., the lens frame of the negative meniscus lens L_{37}, serves as an aperture stop.

The reduction ratio of the overall system is 1/4×, the numerical aperture (NA) on the wafer side (image side) is 0.5, and the object height is 60 mm. The width of the bar-shaped exposure region 24A on the wafer W, shown in FIG. 10, in the scanning direction is 4 mm.

One type of optical glass consisting of fused quartz is used for all the refracting lenses. The system is corrected for axial chromatic aberration and for chromatic aberration of magnification with respect to a wavelength width of 1 nm in the wavelength (193 nm) of an ultraviolet excimer laser beam. In addition, spherical aberration, coma, astigmatism, and distortion are corrected to attain an almost aberration-free state, thereby realizing an optical system having excellent imaging performance.

The curvature radii r_i, plane distances d_i, and glass materials used in the third embodiment shown in FIG. 23 are shown in Table 3. In Table 3, the 34th plane is a virtual plane indicating the reflecting surfaces of the concave reflecting mirror M_1.

TABLE 3

i	r_i	d_i	Glass Material	i	r_i	d_i	Glass Material
0	—	33.7		33	−198.40	11.1	
1	115.52	24.0	SiO_2	34	∞	0.0	
2	201.62	3.0		35	125.71	11.1	
3	102.72	21.0	SiO_2	36	198.40	8.5	SiO_2
4	79.03	54.0		37	76.19	161.4	
5	−69.98	9.0	SiO_2	38	∞	55.0	
6	−831.37	9.0		39	−2718.54	18.0	SiO_2
7	−158.10	36.0	SiO_2	40	−114.25	3.0	
8	−87.19	24.0		41	201.91	24.0	SiO_2
9	189.29	48.0	SiO_2	42	−214.05	3.0	
10	−178.69	7.0		43	−1582.73	15.0	SiO_2
11	−153.53	24.0	SiO_2	44	309.83	12.0	
12	−169.00	6.0		45	−337.52	28.2	SiO_2
13	131.04	13.4	SiO_2	46	−156.44	30.4	
14	78.51	45.0		47	225.73	28.0	SiO_2
15	−69.71	18.0	SiO_2	48	−1363.11	3.0	
16	−117.02	3.0		49	150.18	18.0	SiO_2
17	303.29	36.1	SiO_2	50	426.42	27.0	
18	−172.25	17.6		51	−167.12	16.8	SiO_2
19	−174.43	30.0	SiO_2	52	−719.40	48.0	
20	−156.46	18.0		53	−259.90	24.7	SiO_2
21	−206.73	27.0	SiO_2	54	−158.30	15.0	
22	−177.68	64.8		55	−88.33	20.2	SiO_2
23	275.50	36.0	SiO_2	56	−88.58	1.5	
24	−127.44	26.8		57	492.66	24.0	SiO_2
25	−84.26	18.0	SiO_2	58	1972.64	1.5	
26	−181.22	12.0		59	136.67	30.0	SiO_2
27	−58.86	24.0	SiO_2	60	−999.05	1.5	
28	−66.54	12.2		61	66.51	34.0	SiO_2
29	69.08	33.0	SiO_2	62	166.37	4.5	
30	668.69	97.5		63	321.60	11.2	SiO_2
31	∞	161.4		64	168.79	18.4	
32	−76.19	8.5	SiO_2				

FIGS. 24 and 25 respectively show longitudinal aberration charts in the third embodiment; FIG. 24 shows an astigmatism of this embodiment; and FIG. 25 shows a distortion of this embodiment. Further, FIG. 26 shows a magnification chromatic aberration chart in the second embodiment. FIGS. 27(a), 27(b) and 27(d) show traverse aberration charts in the third embodiment.

According to the present invention, relations (1) to (6) above are preferably satisfied. The relationship between each of the above embodiments and the relations will be described below. Tables 4 to 6 respectively show the curvature radii r of the concave reflecting mirror M_1, focal lengths f_i of lens groups G_i (i=1 to 3), Petzval sums p_i, imaging magnifications β_i, magnifications β_g of the synthetic systems of the refracting lens groups G_1 and the catadioptric lens group G_2, and magnifications β_3 of the refracting lens groups G_3. Note that each total system is represented by G_T, and a Petzval sum p_t and imaging magnification β of the total system G_T ... columns of "Petzval Sum p_t" and "Imaging Magnification β" corresponding to the total system G_T.

TABLE 4

Specifications of first embodiment

	r	f_i	p_i	n_i	β_i	β_g
G_1	—	1411.25	0.00690	0.10269	−0.47409	0.36471
G_2	−126.038	106.851	−0.02142	−0.43692	−0.76928	
G_3	—	−130.078	0.01462	−0.52583	−0.68386	−0.68386
G_T	—	—	0.00010—		−0.24941	−0.24941

TABLE 5

Specifications of second embodiment

	r	f_i	p_i	n_i	β_i	β_g
G_1	—	1422.107	0.00611	0.115168	−0.46807	0.37808
G_2	−124.838	110.143	−0.02157	−0.420914	−0.807742	
G_3	—	−103.285	0.01565	−0.618653	−0.66108	−0.66108
G_T	—	—	0.00020—		−0.24994	−0.24994

TABLE 6

Specifications of third embodiment

	r	f_i	p_i	n_i	β_i	β_g
G_1	—	1115.522	0.00680	0.131830	−0.43865	0.34218
G_2	−125.712	108.028	−0.02172	−0.426192	−0.780075	
G_3	—	−107.560	0.01490	−0.623969	−0.731048	−0.731048
G_T	—	—	−0.00003—		−0.25015	−0.25015

Further, based on Table 5 to Table 8, values are calculated for (p_1+p_3), p_2, $|p_1+p_2+p_3|$, $|\beta_{12}|$, $|\beta_3|$, and $|\beta|$ in each embodiment, and the following Table 9 shows the calculated values.

TABLE 7

Table of correspondence conditions

Conditions/Embodiment	1	2	3
(1) $p_1 + p_3 > 0$	0.02152	0.02176	0.02170
(2) $p_2 < 0$	−0.02142	−0.02157	−0.02172
(3) $\left| p_1 + p_2 + p_3 \right| < 0.1$	0.00010	0.00020	0.00003
(4) $0.1 \leq \left| \beta_1 \right| \leq 1$	0.47409	0.46807	0.43865
(5) $0.5 \leq \left| \beta_2 \right| \leq 2$	0.76928	0.80774	0.780075
(6) $0.25 \leq \left| \beta_3 \right| \leq 1.5$	0.68386	0.66108	0.731048

As is apparent from the above tables, relations (1) to (6) given above are satisfied in each of the above embodiments.

In each embodiment described above, as the half mirror, a compact mirror covering a half portion of the optical axis is used. However, as the half mirror, a partial reflecting mirror constituted by a large glass plate and having a reflecting film formed on only one surface side of the optical axis may be used. Alternatively, as the half mirror, a prism type beam splitter having a reflecting film formed on only, e.g., the lower half portion of the joined surface serving as a reflecting surface may be used.

In each embodiment described above, quartz is used as a glass material for a refracting optical system. However, optical glass such as fluorite may be used.

Next, an embodiment of a common exposure apparatus using the catadioptric reduction projection optical system 5